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Surface roughness is known to have a significant impact on turbine heat loads and performance. Over time, as the turbine blades are exposed to these loads, the external surfaces become rougher, which results in increased heat loads and friction losses. The objective of the present investigation is to conduct measurements that will reveal the influence of *realistic* surface roughness on the near-wall behavior of the boundary layer. LDV measurements have been conducted in a Matched-Index-Of-Refraction (MIR) oil tunnel. The tunnel has been modified to operate with an accelerating freestream and an elevated freestream turbulence level in order to simulate conditions on the suction side of a high pressure turbine blade. We have made extensive boundary layer measurements over a smooth plate model and over a model with a strip of realistic rough surface. The realistic rough surface was developed by scaling actual turbine blade surface data that was provided by AFRL. The results include velocity profiles, streamwise and vertical turbulence intensity profiles, and Reynolds stress profiles. The oil tunnel arrangement has permitted velocity measurements very close to the wall (down to $y^+ < 1$). These detailed results should be valuable to assess and guide development of computational fluid dynamics predictions.

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THE BOUNDARY LAYER OVER TURBINE BLADE MODELS WITH REALISTIC ROUGH SURFACES

Final Report

AFOSR Grant Number: F49620-00-1-0265

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Abstract

Surface roughness is known to have a significant impact on turbine heat loads and performance. Over time, as the turbine blades are exposed to these loads, the external surfaces become rougher, which results in increased heat loads and friction losses. The objective of the present investigation is to conduct measurements that will reveal the influence of *realistic* surface roughness on the near-wall behavior of the boundary layer. LDV measurements have been conducted in a Matched-Index-Of-Refraction (MIR) oil tunnel. The tunnel has been modified to operate with an accelerating freestream and an elevated freestream turbulence level in order to simulate conditions on the suction side of a high pressure turbine blade. We have made extensive boundary layer measurements over a smooth plate model and over a model with a strip of realistic rough surface. The realistic rough surface was developed by scaling actual turbine blade surface data that was provided by AFRL. The results include velocity profiles, streamwise and vertical turbulence intensity profiles, and Reynolds stress profiles. The oil tunnel arrangement has permitted velocity measurements very close to the wall (down to $y^+ < 1$). These detailed results should be valuable to assess and guide development of computational fluid dynamics predictions.

Objectives

Surface roughness is known to have a significant impact on turbine heat loads and performance. Over time, as the turbine blades are exposed to these loads, the external surfaces become rougher, which results in the increase of heat loads and friction losses. While there have been several investigations that included surfaces with uniform or two-dimensional roughness patterns there is now a clear need to measure the influence of *realistic surface* roughness on turbine blade flow and heat transfer.

The objective of the present investigation is to conduct measurements that will reveal the influence of *realistic surface* roughness on the near-wall behavior of the boundary layer. The test surface is a large-scale version of rough surfaces that has been specified by the Air Force Research Laboratory/Propulsion Directorate. That is, a geometric model of a real surface has been be employed but in much larger size so we can obtain high quality

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velocity and turbulence data in the near-wall region, including the viscous layer. Thus, the measurements obtained are related to convective heat transfer from the surface. Since the near-wall region is still subsonic in a transonic boundary layer, such detailed measurements should be valuable to assess and guide development of computational fluid dynamics models proposed for predictions of flows over realistic surfaces in gas turbine passages at engine operating conditions.

Approach

The MIR Facility: The measurements have been conducted in the Matched-Index-of-Refraction (MIR) Facility at the Idaho National Engineering and Environmental Laboratory (INEEL), the largest MIR Facility in the world (Stoots et al., 2001). Optical flow measurement techniques permit flow field determination without locating transducers in the flow. By using transparent models, complex flow fields can be studied and the results can be used to assess the validity of computational fluid dynamic codes for difficult conditions. However, refraction of light beams can distort the views, introduce positioning errors and block measurements in some desired regions. A solution to these difficulties is to match the indices of refraction of the model and the fluid so that light rays are not deflected. While the INEEL MIR flow system has the refractive index matching advantage that permits measurements that would otherwise be impossible, its innovation and technical significance is its large size.

The MIR flow system employs a light mineral oil as the working fluid. Current instrumentation includes a two-component fiber optics LDV, a computer-controlled three-directional traversing mechanism, hot-film anemometers, a computer data acquisition system with LabView software and typical temperature and pressure sensors. A parallel auxiliary flow loop with an electric heater and a heat exchanger is employed with computer feedback control in order to maintain a selected, steady temperature in the system.

Maximum velocity in the current test section is about two meters per second. Qualification measurements with hot film sensors and with the LDV showed the freestream velocity profile to be uniform to within one per cent and the free-stream turbulence level was 0.5 to 0.8 per cent without tripping. Fluid temperature is maintained to within 0.04 C to control its refractive index.

Overview of Apparatus: Figure 1 is a schematic drawing of the experimental apparatus that has been designed, constructed, and installed in the MIR Facility. The individual components of this apparatus are described in subsequent paragraphs. The MIR Facility test section is a 0.61 meter square channel 2.4 meters long. It is made of 3.8 cm thick transparent polycarbonate on all sides. The test section is divided into three equal compartments. Each compartment has a glass window positioned in the center of both vertical sidewalls to improve optical access. The flow medium in this experiment will be light mineral oil. The mineral oil flows from left to right in the diagram. A turbulence generator is located upstream of the test section. The test plate is constructed of aluminum and quartz and is supported by five steel supports. An additional aluminum plate is installed above the test plate to achieve the desired streamwise pressure gradient

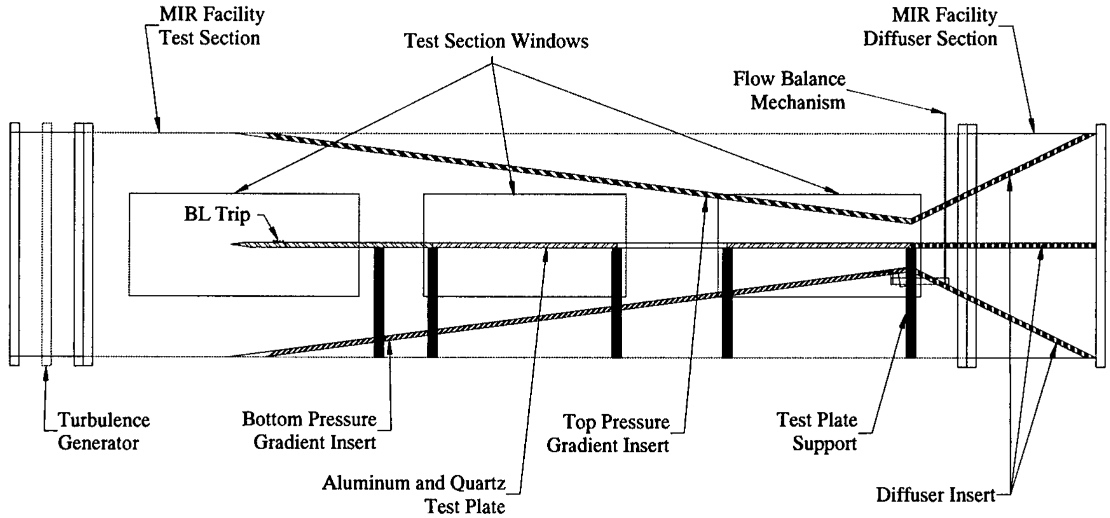

Figure 1. Schematic illustration of the test section with model installed.

in the flow, and a similar plate is installed beneath the test plate to provide balance and to control flows on the upper and lower surface of the test plate. Finally, a diffuser is installed at the end of the test plate to prevent excessive losses in the flow loop.

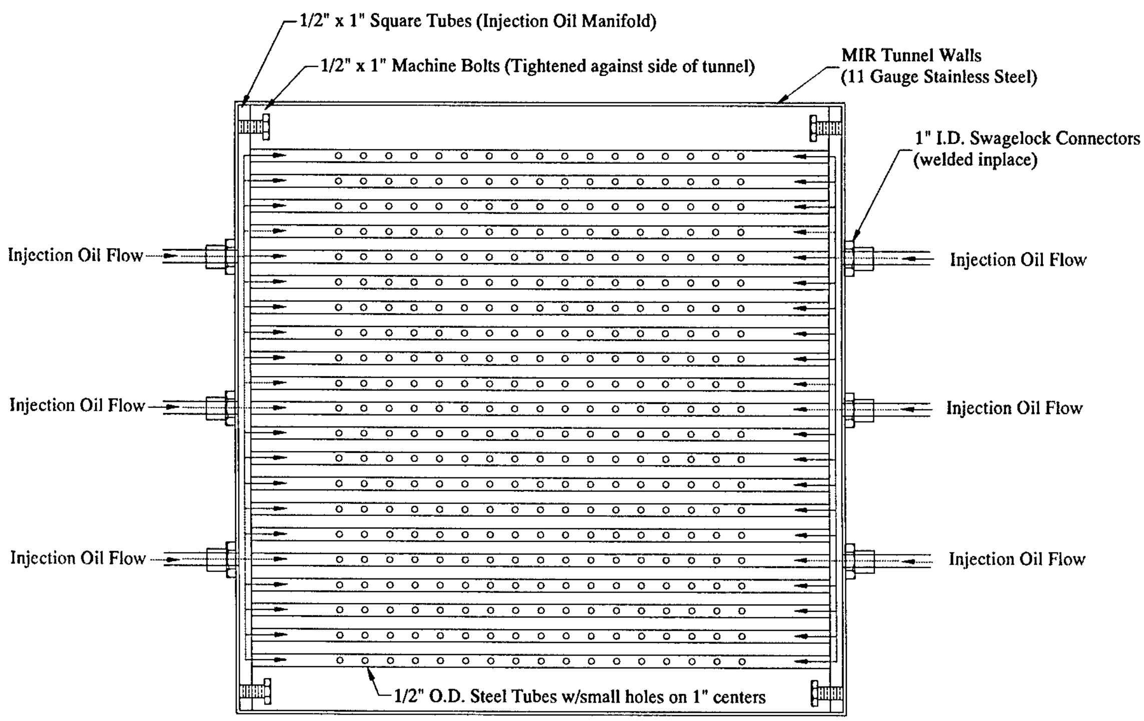

Figure 2. Schematic drawing of active grid turbulence generator.

<u>Turbulence Generator:</u> Figure 2 is a drawing of the turbulence generator – it is an active grid of 21 parallel tubes that has been installed 5.1 cm upstream of the test section. The tubes are spaced on 2.54 cm centers (M = 2.54 cm) and have small holes on the *downstream* side of the array for secondary flow injection. Injection oil is provided through a parallel auxiliary flow loop powered by a separate pump. According to Welsh et al. (1997) and relationships developed by Roach (1987), this active grid should produce a free-stream turbulence intensity (Tu) of about 9-10% at the leading edge of the test plate (46 cm downstream from the turbulence generator). Also, in accordance with the findings of Blair (1982) and Young et al. (1992), the turbulence at 20 grid mesh lengths downstream (x/M=20) should be homogeneous. In the present apparatus the leading edge of the plate is located at x/M = 18.

<u>Smooth Test Plate and Pressure Gradient Inserts</u>: The test plate for these experiments is made of three sections of 1.3 cm thick aluminum plate and two sections of 1.3 cm thick GE124 clear fused quartz. The first section of the test plate is a 15.2 cm long with the leading edge machined into the shape of a NACA 009 airfoil. A turbulence trip is located 12.7 cm downstream of the leading edge. The trip consists of the four staggered rows of vertical dowel pins across the plate. The trip was designed to simulate the boundary layer disturbances due to the film cooling jets that are located near the leading edge of a turbine blade. The quartz sections are installed so that they are centered in the middle and end glass windows of the test section. The top and bottom pressure gradient inserts are made of 1.3 cm thick aluminum plate and are placed in the test section to produce an acceleration parameter, $\boldsymbol{K} = (\nu/U_\infty^2)(dU_\infty/dx)$, of approximately 3×10^{-6}. This value of $\boldsymbol{K}$ is important because we are attempting to model flow over the first 1/3 of the suction side of a high-pressure turbine vane. We estimated the appropriate value of $\boldsymbol{K}$ by applying potential flow analysis to a circular cylinder model with typical at-altitude high-pressure turbine inlet conditions. This estimate established that $\boldsymbol{K}$ values in the range of 1×10^{-6} to 4×10^{-6} were desired. Additionally, Blair (1983), Keller and Wang (1996), Volino and Simon (1997), Zhou and Wang (1996) and others have conducted related boundary layer studies with K ranging from 0.2×10^{-6} to 4.1×10^{-6}. The value in the present study, $\boldsymbol{K} = 3 \times 10^{-6}$, represents a typical dimensionless acceleration that is found on suction side of a turbine vane over the first one-quarter of the blade.

<u>Realistic Rough Surface Test Plate</u>: We have completed and implemented the detailed design for a realistic rough surface model. The model is patterned after a suction side surface that was evaluated by Bons et al. (2001). We developed a method for scaling the actual turbine blade roughness onto our laboratory model (McIlroy et al., 2003). In this method, we first estimate the non-dimensional roughness (in wall coordinates) for a turbine blade at operating conditions. We then adjust the scale of the roughness on the laboratory model so that the same non-dimensional roughness is achieved. This method has yielded a scale factor of 96 for the present experiment.

A 4 inch by 20 inch (streamwise by spanwise, respectively) strip of realistic rough surface (RRS) was constructed by scaling surface data provided by AFRL (Professor Jeffrey Bons). The data were scaled and converted to x,y,z format in a custom C++ program. A solid model was then generated using Rhino 3-D and saved as an .iges file.

The .iges file was transferred to MasterCam in order to generate G-code to drive a CNC miling machine. This 47 Mbyte G-code file was broken into 45 segments for the actual milling operation, which took 27 hours to complete. Figure 3 shows the aluminum realistic rough surface with quartz plates on either side – all installed in the test section of the oil tunnel. The upstream edge of the RRS was located 650 mm downstream of the leading edge of the plate.

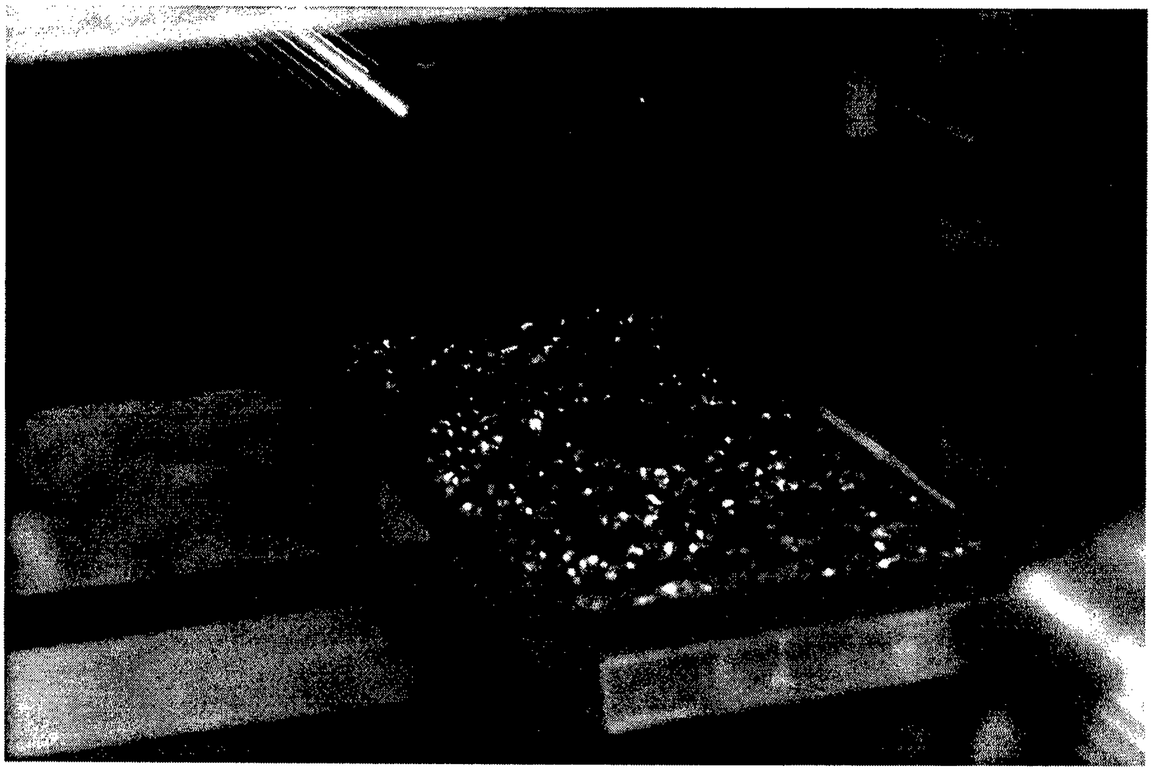

Figure 3. The realistic rough surface installed in the test section of the oil tunnel.

Results

Characterization of the Freestream: The freestream velocity and dimensionless parameters for these experiments are shown in Figure 4. The resulting K and Reynolds number values are in the correct range for the first 1/3 of the suction side of a high-pressure turbine vane. We also checked the spanwise uniformity at two streamwise locations and found the mean velocity to be uniform within 2% across the central 16 cm of the plate. The graph in Figure 5 shows the freestream turbulence intensity that was generated by an active grid at the entrance to the test section. We have achieved a turbulence intensity of over 5% at the leading edge of the plate – to model the elevated turbulence intensity that is found at the entrance to a high pressure turbine. The results in Figure 5 reveal that the turbulence intensity decays in the downstream direction. This result is as anticipated and is due to freestream acceleration and to viscous dissipation.

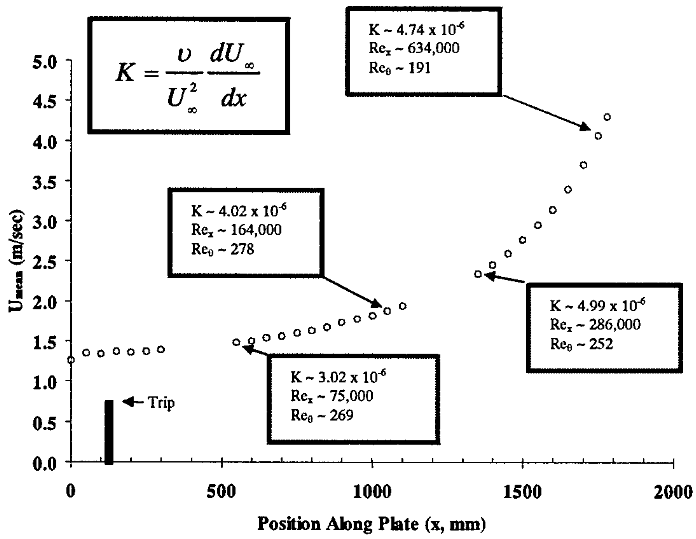

Figure 4. Freestream velocity and dimensionless parameter results for the smooth plate baseline study.

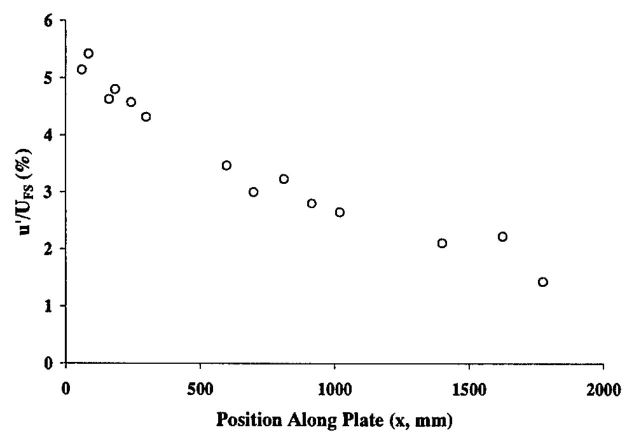

Figure 5. Freestream streamwise turbulence intensity results for the smooth plate baseline study.

The Smooth Plate Boundary Layer: Boundary layer measurements were conducted at eight locations along the plate. Results include velocity profiles, streamwise and vertical turbulence intensities, and Reynolds stress. Selected results are presented in this final report. Figure 6 is a graph of the boundary layer velocity profiles. The wall shear stress was estimated from the slope of the profile very near the wall. Figure 7 is graph of the velocity profile at $x = 812$ mm in wall coordinates. In the oil tunnel it is possible to obtain velocity measurements (u and v) very close to the wall (down to $y^+ < 1$).

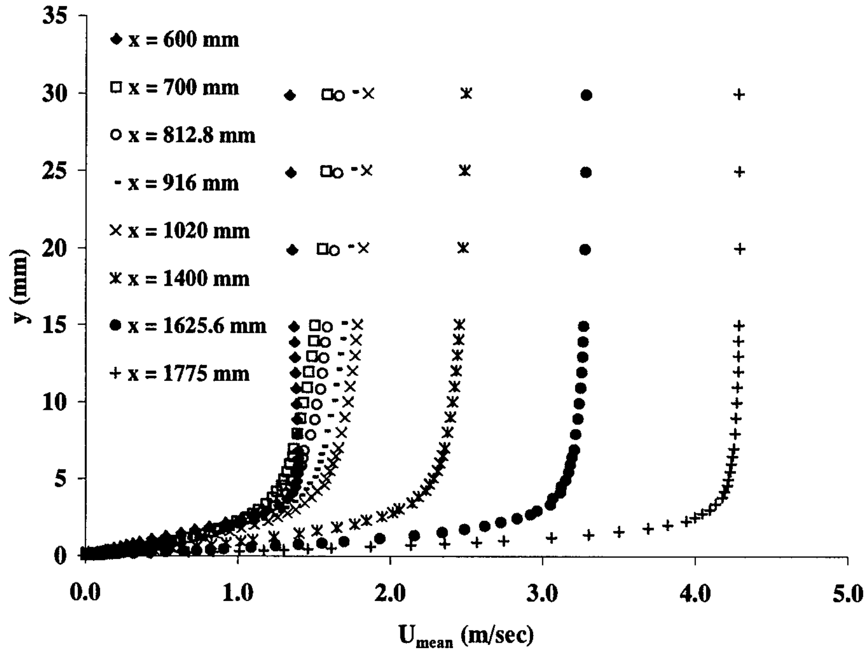

Figure 6. Boundary layer velocity profiles.

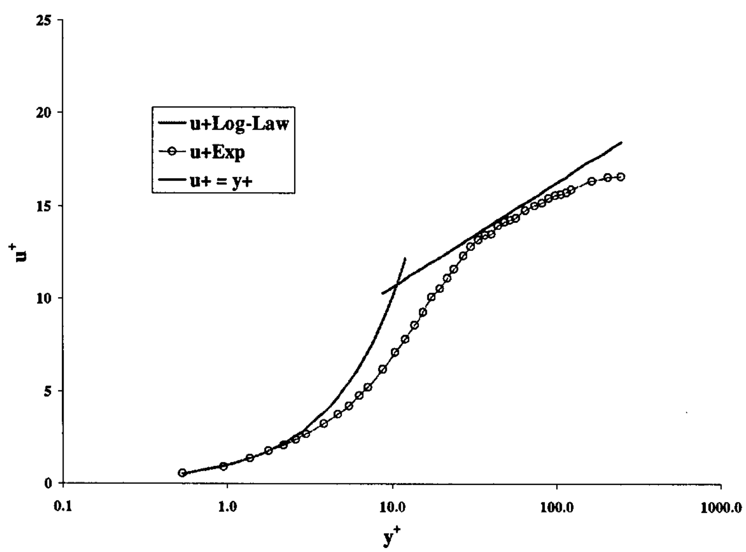

Figure 7. The boundary layer profile at x = 812 mm in wall coordinates.

Figure 8 is a plot of the development of the skin friction coefficient along the plate. The solid line is a plot of the theoretical skin friction coefficient obtained by using a 4th order polynomial fit to the freestream velocity curve in Figure 2 and the correlation method of Thwaites (1949). This polynomial input into the Thwaites method produces a theoretical skin friction coefficient, C_f, for a **laminar** boundary layer in accelerating flow. The open circles are values of the skin friction coefficient, C_f, calculated from our experimental measurements. The experimental values of C_f rise above the theoretical laminar curve

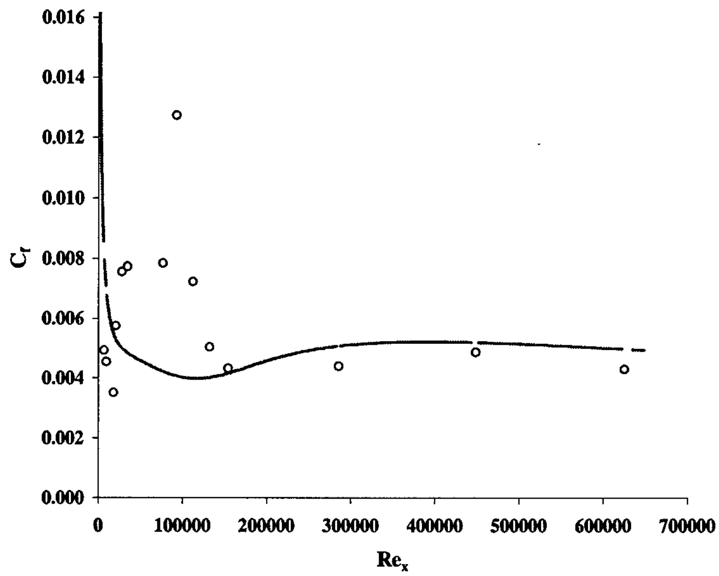

Figure 8. Development of the skin friction coefficient along the plate.

for the range $5 \times 10^4 < Re_x < 1.5 \times 10^5$ indicating that the boundary layer is *transitional* over this range. The data points beyond $Re_x = 1.5 \times 10^5$ are just below the theoretical curve – indicating that the boundary layer has *relaminarized.* This relaminarization is due, presumably, to the strong favorable pressure gradient.

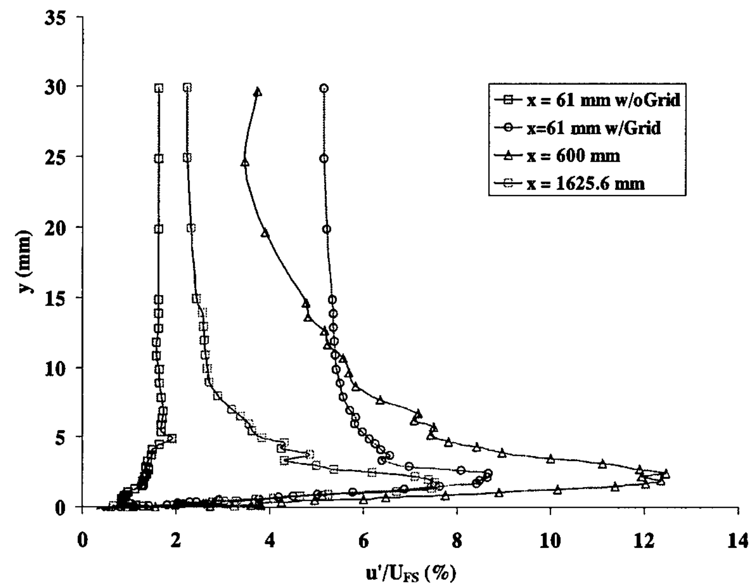

Figure 9. Streamwise turbulence intensity profiles in the boundary layer.

Figure 9 is a plot of streamwise turbulence intensity profiles in the boundary layer at three locations along the plate. The x = 61 mm profile reveals the turbulence intensity in the boundary layer is elevated, even before the trip, when the turbulence generating grid is installed. The corresponding turbulence intensity profile (at x = 61 mm) **without the grid** installed is not elevated. This indicates that *bypass transition* occurs when the elevated freestream turbulence is present. The x = 600 mm profile has a higher turbulence intensity than the x = 1626 mm profile. This is due to the relaminarization of the boundary layer noted above (in the discussion of Figure 8).

<u>The Rough Plate Boundary Layer</u>: Boundary layer measurements were conducted at 25 locations along the plate, including one location upstream of the realistic rough surface (RRS), 15 over the RRS, and nine downstream of the RRS. Results upstream and downstream of the RRS include velocity profiles, streamwise and vertical turbulence intensities, and Reynolds stress. Results over the RRS only include streamwise velocity and turbulence intensity, since it was not possible to measure the vertical velocity component directly over the aluminum RRS. The rough plate boundary layer results are being analyzed at the time of the writing of this final report. Selected preliminary results are shown below.

Figure 10 is a comparison of boundary layer velocity profiles between the smooth surface baseline flow and the RRS flow at three locations. Upstream of the RRS (Figure 10a) the

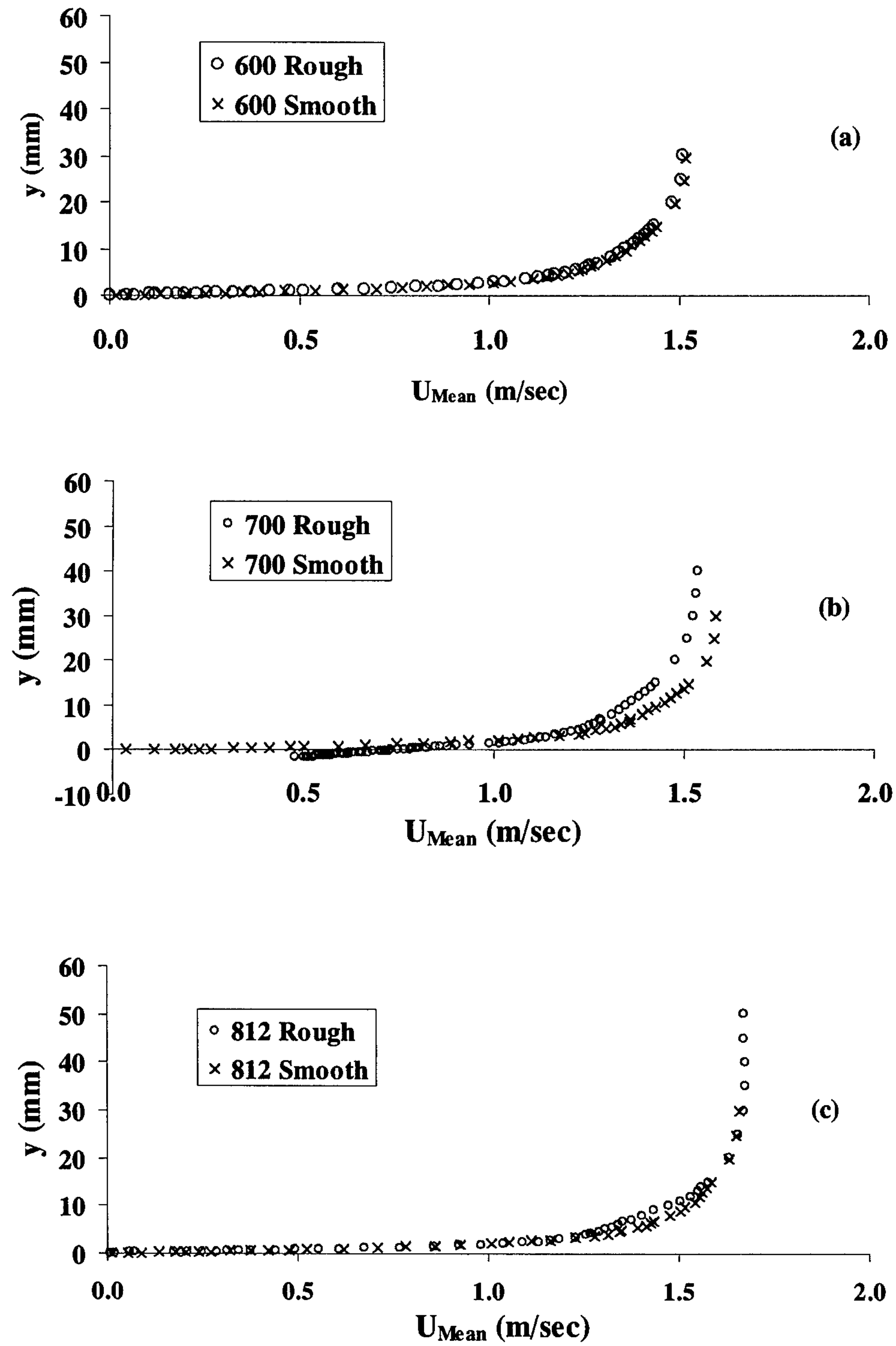

Figure 10. Comparison of boundary layer velocity profiles between the smooth surface baseline flow and the realistic rough surface at three locations: (a) just upstream of the RRS, (b) over the RRS, and (c) downstream of the RRS.

baseline and RRS velocity profiles are nearly identical. This simply confirms that we have matched the flow conditions coming into the RRS to be the same as the smooth surface baseline flow conditions were at that location. Note that the mean velocity profile over the RRS (Figure 10b) has data points that are below the plane of the smooth surface that is upstream and downstream of the RRS. These points, with negative y values, are velocity measurements in a valley of the RRS. Figure 10b also reveals that the mean velocity at a given height above the RRS is lower than the corresponding baseline value. Downstream of the RRS (Figure 10c) the baseline velocity profile and RRS velocity profile are similar except for a region from 5 to 15 mm above the surface.

Figure 11 is a comparison of the streamwise turbulence intensity profile between the smooth surface baseline flow and the RRS. The data indicates a increase in the maximum turbulence intensity from about 13% over the smooth surface to about 16% over the RRS.

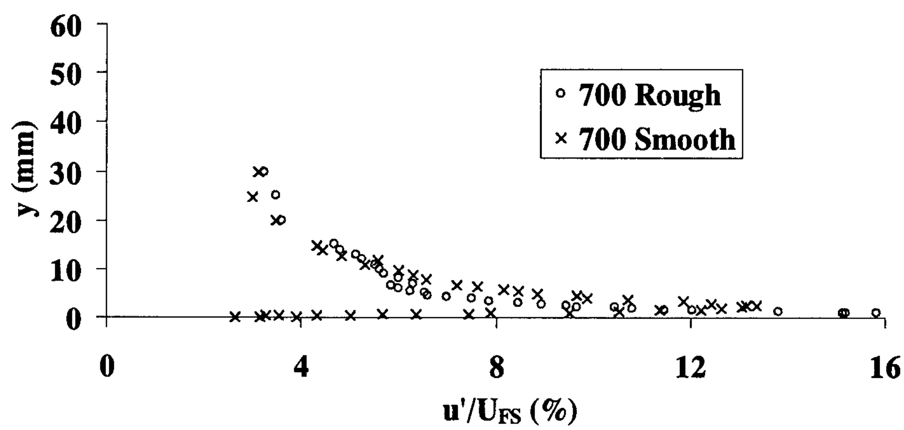

Figure 11. Comparison of streamwise turbulence intensity profiles between the smooth surface baseline flow and the RRS.

Future Plans

During the spring of 2004 we plan to complete the analysis of the boundary layer profile measurements upstream, over, and downstream of the realistic rough surface. We will then make comparisons to the baseline smooth flat plate results.

Acknowledgement /Disclaimer

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Publications

W.J. Dalling, "An Experimental Study of Wall Shear Stress on Distributed Rough Surfaces in a Turbulent Boundary Layer," University of Idaho Master of Science thesis, June 2003.

H.M. McIlroy, Jr., R.S. Budwig, and D.M. McEligot, 2003, "Scaling of Turbine Blade Roughness for Model Studies," presented at IMECE'03, paper IMECE2003-42167, Washington, D.C., November 2003.